Discharge Chamber Measurements of an Annular Ion Engine

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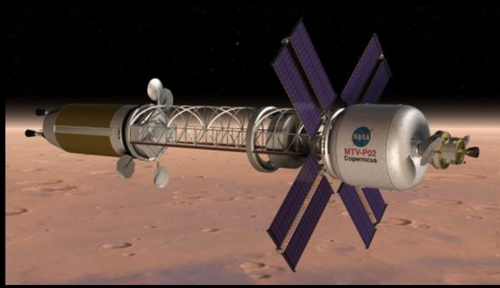

Outline

- What are the performance characteristics and limitations of SOA Ion Engines?

- What potential advantages might the Annular Engine (AE) approach provide in extending the performance capabilities of Gridded Ion Thrusters?

- Development status of the Annular Engine
  - Brief review of GEN1 (42 cm O.D.) Engine results
  - Recent tests completed on GEN2 (65 cm O.D.) Engine

- FY15 Plan

Limitations of SOA Ion Engines

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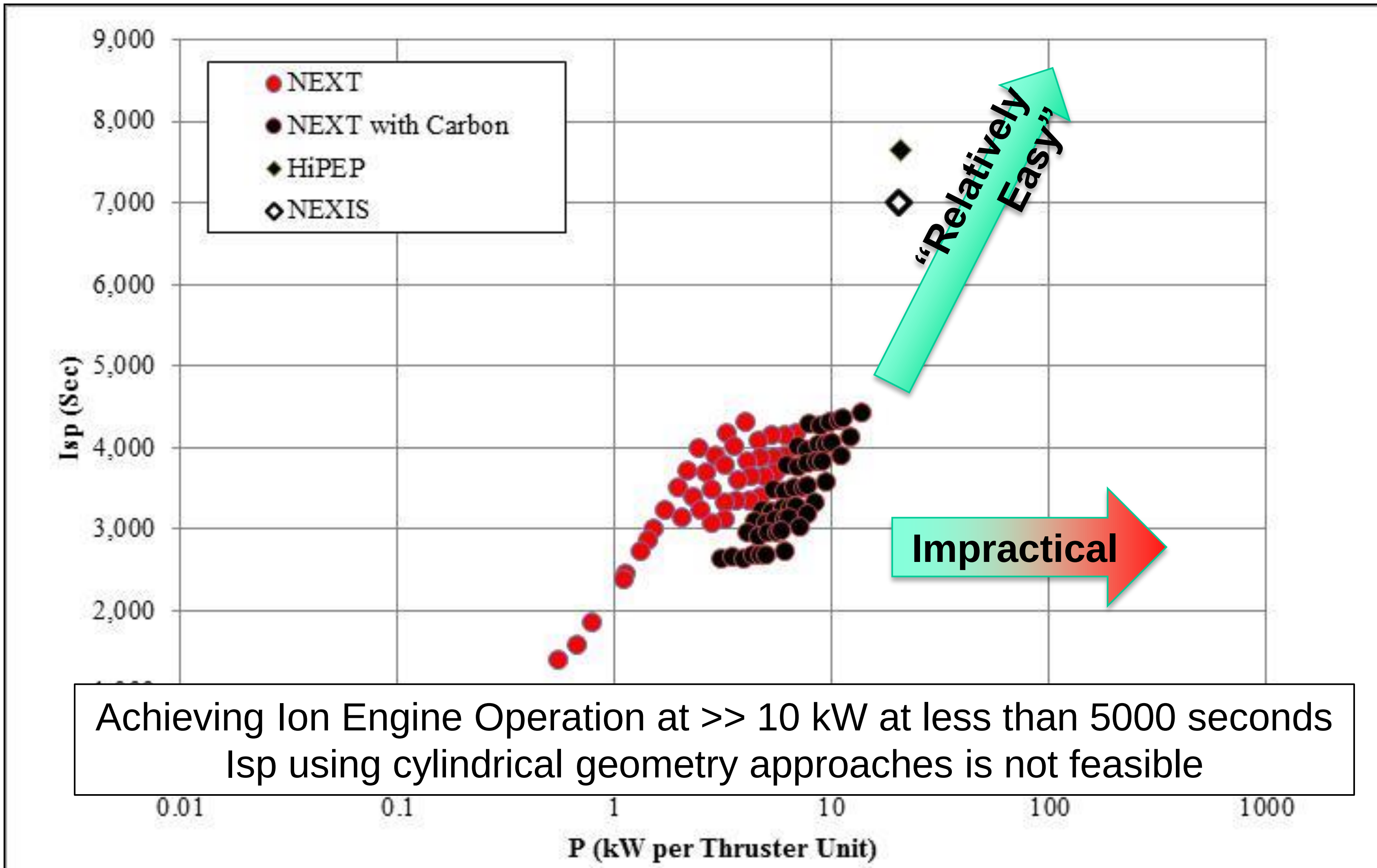
- Discharge plasma uniformity/stability
- Limited span-to-gap ratio



Achieving Ion Engine Operation at >> 10 kW at less than 5000 seconds Isp using cylindrical geometry approaches is not feasible

Achieving High Thrust Density

- An electrostatic ion thruster thrust density, F_A, thrust per unit area in N/m^2, is given by:

$$F_A = \gamma (2\frac{m}{q})^{0.5} I_b (V_b)^{0.5} / A_b$$

- For a given specific impulse, I_{sp}, the thrust density is then proportional to the product of the total thrust-loss correction factor and the ion beam current density, J_b:

$$F_A \propto \gamma \cdot J_b$$

- Where thrust density is maximized as γ approaches unity and J_b is maximized

- Several limitations on achievable ion current density

  - extraction capability of ion optics

  - source production

ACHIEVING HIGH THRUST DENSITY (OPTICS LIMITATIONS)

- The ion beam current density is established by the current extraction capability of the thruster ion optics, described by the Child-Langmuir equation:

$$J_b = \left(\frac{4\varepsilon_o}{9}\right)\left(\frac{2q}{M}\right)^{1/2} \frac{V_t^{3/2}}{l_e^2}$$

- The expression for ion optics beam current density reduces to:

$$J_b \propto \frac{V_t^{3/2}}{(l_g + t_s)^2 + (d_s/2)^2}$$

- Where current density is maximized as the total voltage is increased to the highest practical value, and l_g, t_s, and d_s electrode geometric parameters are reduced to practical limits

  l_g = interelectrode gap t_s = screen grid thickness d_s = screen aperture diameter

- practical limit for span to gap ratio for conventional engines ~ 650-700

Achieving High Thrust Density (Source Limitations)

Other design constraints may limit thrust densities to values below those predicted by operation near the Child-Langmuir equation; in particular the maximum supportable discharge (anode) current

Ring-cusp magnetic circuits implemented in SOA thrusters limit the anode area which collects electron current from the plasma:

- Maximum thrust and thrust density demonstrated for the 40 cm NEXT thruster is 0.466 N and 5.7 N/m^2 corresponding to an anode current of about 32 Amperes, whereas
- The maximum thrust and thrust density demonstrated for a 30 cm thruster with divergent-field is 0.577 N and 11.2 N/m^2 at an anode current of about 63 Amperes

ADVANTAGES OF THE ANNULAR ENGINE

Concept Attribute	Technical Description
3X Increase in Thrust Density	The annular discharge chamber increases the effective anode surface area for electron collection as compared to a conventional cylindrically-shaped ion thruster of equivalent beam area. This attribute allows operation at higher discharge currents and therefore high beam currents yielding an increase in thrust density (up to 3X) and enabling near full-perveance capability of the optics. An annular-geometry flat electrode may enable further electrostatic refinements yielding higher-perveance designs with even higher thrust densities.
>10X Increase in Power	Instead of spanning a large discharge chamber diameter, an annular design enables a very large beam area with relatively small electrode spans and relatively small span-to-gap ratios. This mitigates the manufacturing, mechanical, and thermal challenges of large span spherically-domed conventional ion optics, typically limited to about 600:1 span-to-gap.
Improved Efficiencies	Annular-geometry ion optics of small span may have sufficiently-high natural frequency to implement flat electrodes. Flat electrodes will inherently yield improved efficiencies by eliminating off-axis beam vectoring associated with spherically-domed ion optics electrodes used on cylindrical thrusters; ~3-4 percentage point increase in efficiency across the I_{sp} range.
10X Increase in Life	Because of the relatively-simple physical design of the electrodes for an AGI-Engine, the present manufacturing limitations with carbon are circumvented, thereby allowing the practical implementation of carbon and the life time enhancements of this material.

Motivation and Approach

- Deliver a near-term, low-risk, high-power (5-20 kW) EP thruster technology option with the highest T/P, broadest Isp, and highest Total impulse capability – scalable to > 100 kW

- If the expected performance can be demonstrated, then an Annular Engine could meet the needs of all currently conceived NASA, DOD, and commercial missions – at higher performance and reduced cost relative to SOA EP systems

Thrust to Power vs Isp for SOA Electric Propulsion

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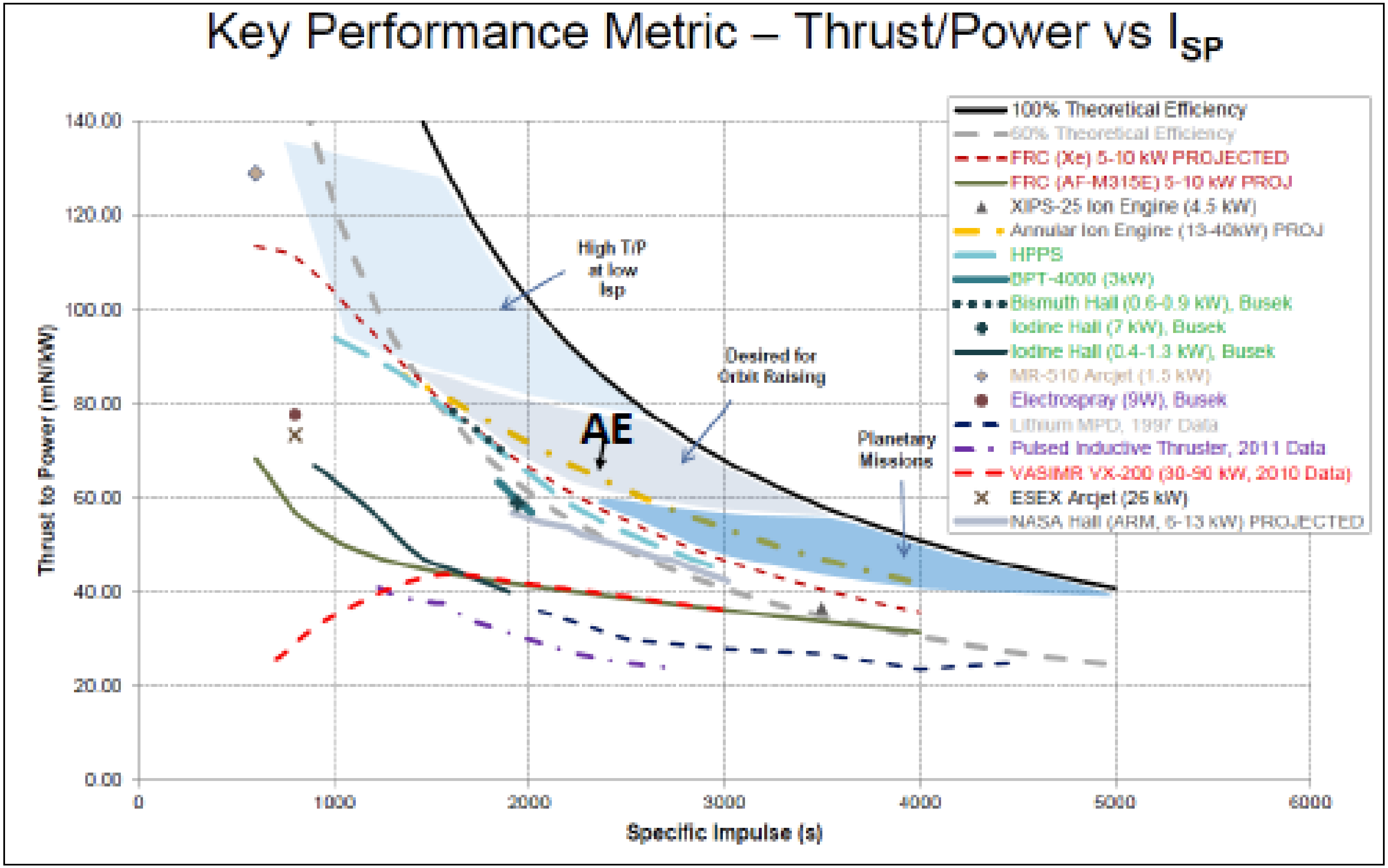


An Annular Engine has high potential EP performance

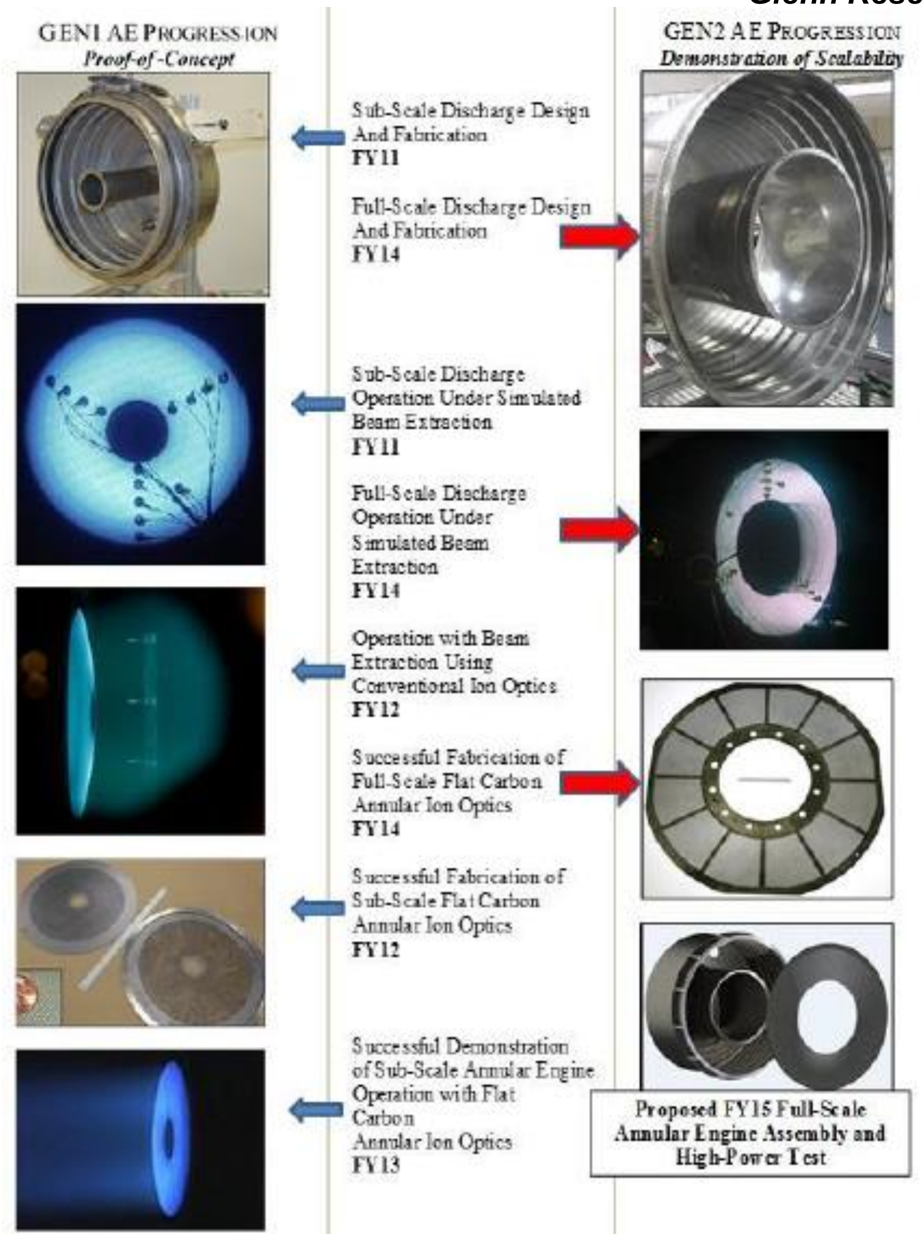
$$F/P_{in} \propto \gamma \frac{V_b^{1/2}}{(V_b + \varepsilon_i)}$$

Annular Engine Development Status

AE Development Cycle and Status

- Achieving high electrical efficiency primary concern
 - large A_{dis}/V_{dis}
 - Asymmetric placement of discharge cathode

- Mitigation strategy:
 - analytical and experimental investigation of discharges losses
 - Optimized discharge magnetic circuit design



Annular Engine GEN1 (42 cm O.D.) Results

Proof-of-Concept Sub-Scale Annular Engine built and tested, successfully completing all technical objectives:

- ✓ Stable Annular Discharge Operation Demonstrated
- ✓ Uniform Annular Plasma Densities Demonstrated
- ✓ High Discharge Efficiency Demonstrated
- ✓ Uniform Beam Current Density Demonstrated
- ✓ Feasibility of Annular, Flat, Carbon-Based Ion Optics at Sub-Scale Demonstrated

Sub-Scale GEN1 Annular Engine Demonstrated the Highest beam flatness (0.085-0.95) and highest beam collimation (0.997) of any EP Thruster Ever

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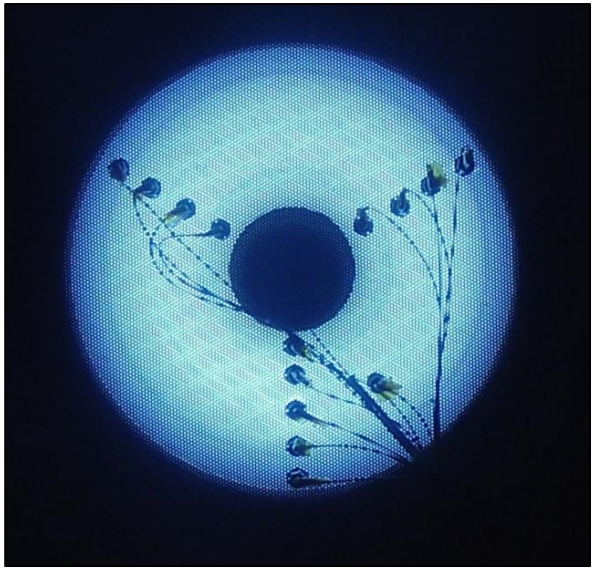

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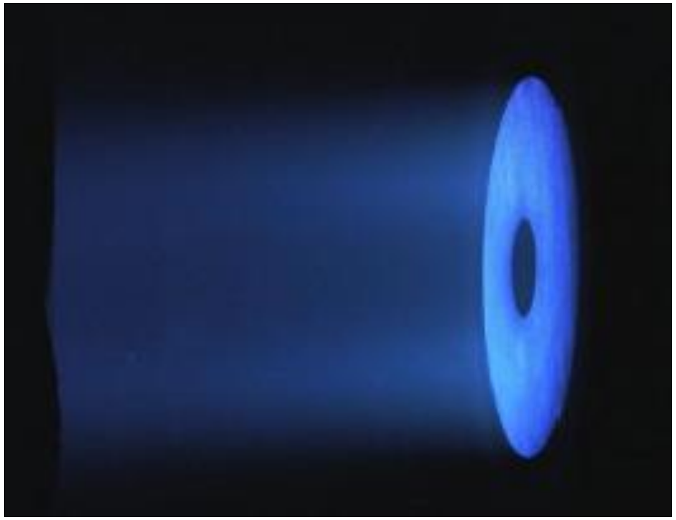

GEN 2 Annular Engine (65 cm O.D.) Development

- GEN2 Engine fabricated to demonstrate scalability of AE to high power
  - scalability of annular discharge chamber and ion optics
  - higher supportable discharge currents and beam current densities than SOA ion engines

- Sized to operate in the 10s kW input power range (65 cm O.D., 36 I.D.)
  - Beam area 2x larger than NEXT, anode area 4x NEXT
  - sized to operate closer to Child-Langmuir limit than SOA ion engines

- Validate uniformity of discharge and beam power with single cathode design

Annular Engine GEN2 (65 cm) Development – Demonstration of Scalability

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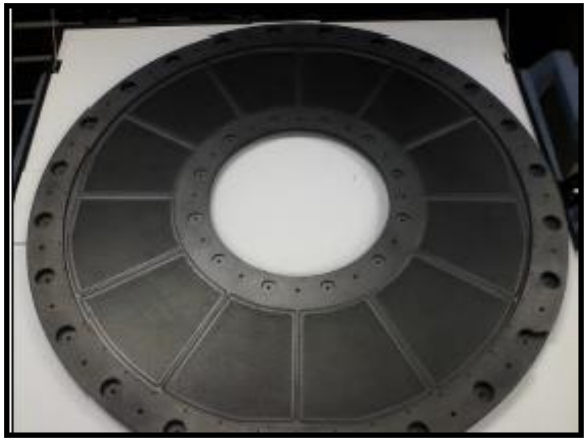
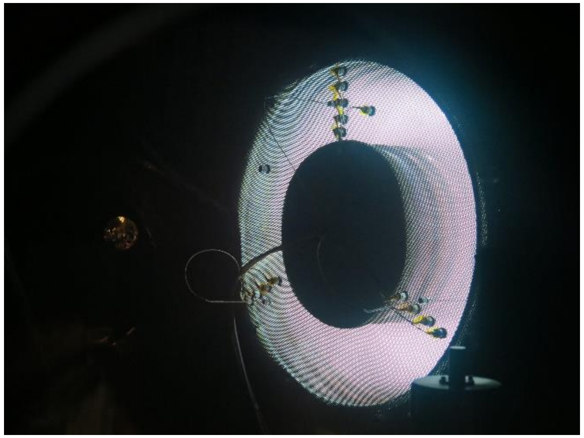


65 cm carbon (PG) Flat
High-Perveance Ion Optics
Successfully Manufactured

20 kW (20 A, 1 kV
Beam Power Supply)
Power
Console in Assembly

65 cm Annular Discharge
Chamber w/
Optimized B-field Fabricated
and Tested



Annular Engine (GEN2) Discharge-Only Tests

- Perforated plate biased to cathode potential to simulate beam extraction
- Executed at Aerospace Corp. Facility (2.4 m dia. x 9.4 m length)
- Three single Langmuir probes were used to assess azimuthal uniformity in the mid-volume of the discharge.
  - Reference probe located just off axis of the main discharge cathode to sample near cathode plume plasma
- Spatial variations in bulk plasma quantified using array of molybdenum button probes
- Thruster input power during initial test limited by current capacity of discharge power supply, intermittent thermally-induced short of perforated cathode potential ‘grid plate’ to anode potential discharge chamber

Electrostatic Probe Location

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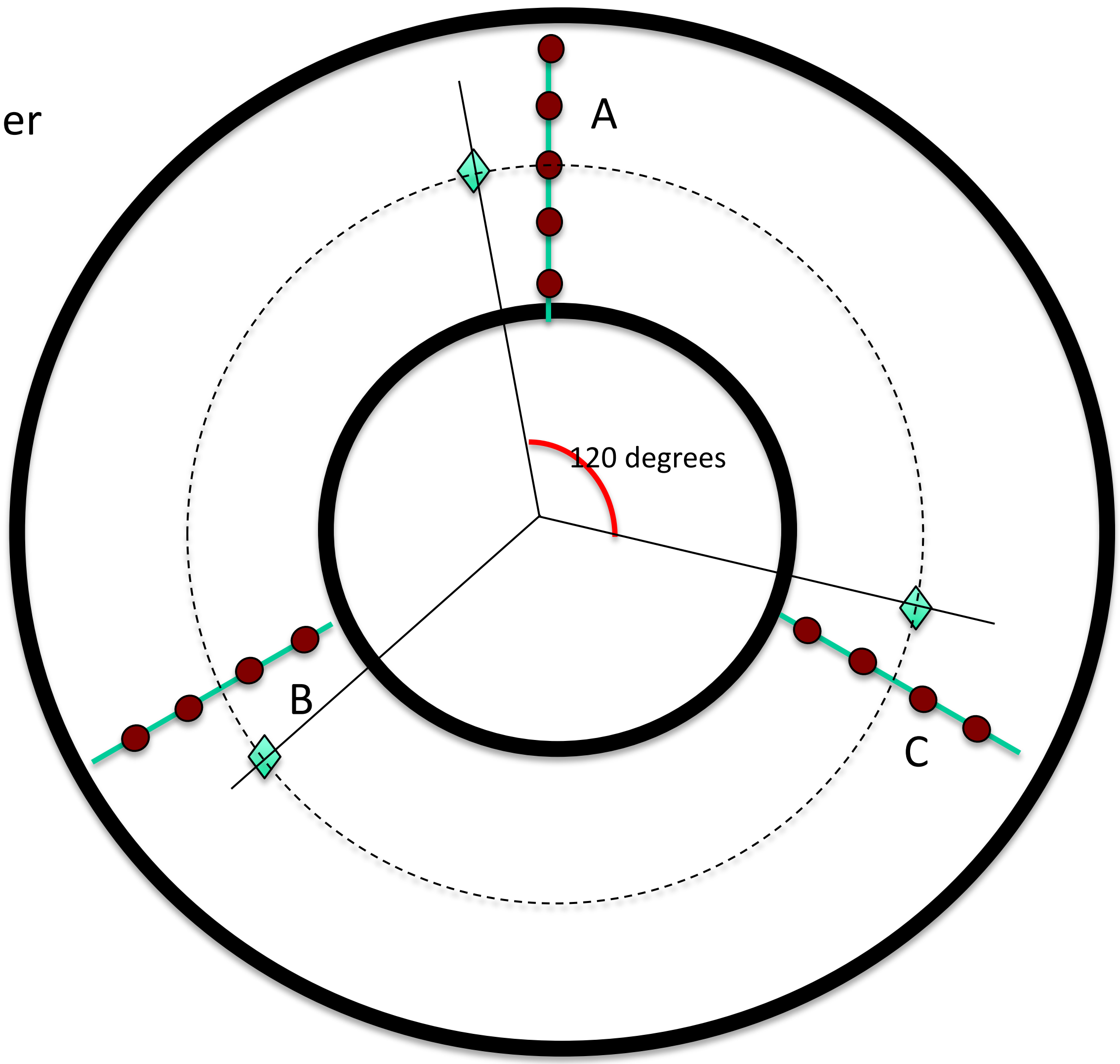
● Grid Button Probes

◇ Langmuir Probe-located midway into discharge chamber

1. Button probes located along three clock positions (A,B, C—clocked 120 degrees apart
2. Line connecting probes at position A intersects cathode axis, with one button probe actually located on centerline with the cathode
3. Spacing between probes on line A is approximately 2.54 cm; spacing between probes along line B and C are 3.9 cm



Discharge Chamber Bulk Plasma Uniformity

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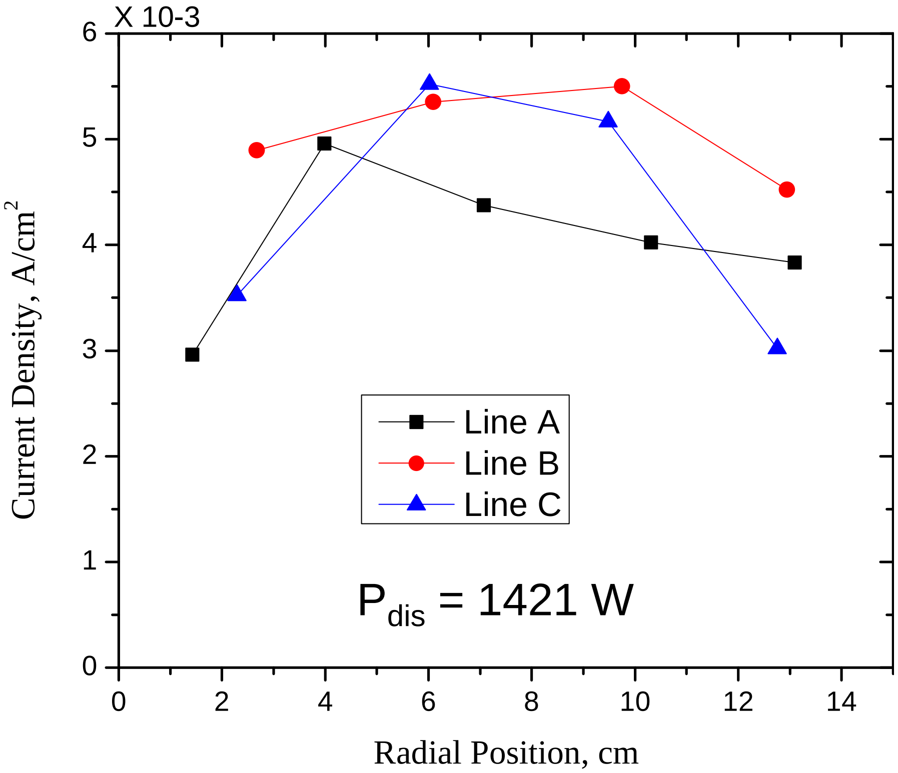
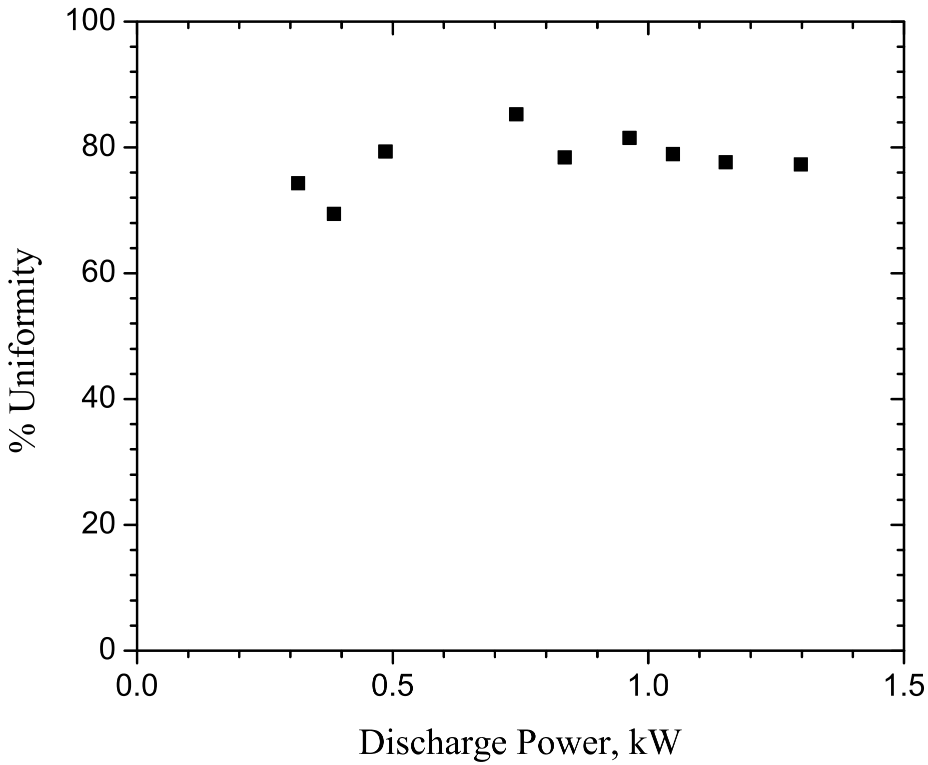
- Excellent overall plasma uniformity, is expected to increase at higher power levels
- Single cathode design approach validated

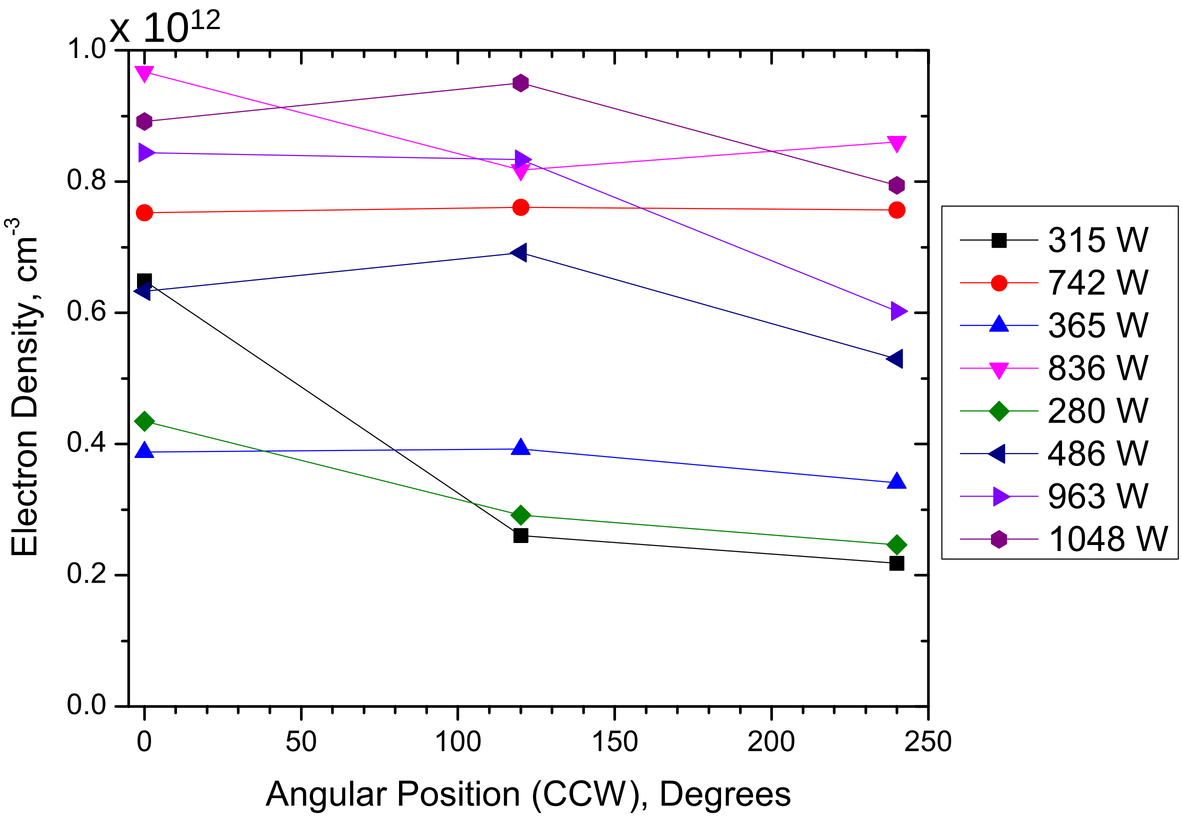
$$\% \text{ Uniformity} = \left(1 - \frac{\frac{j_{b,max} - j_{b,min}}{2}}{\frac{j_{b,max} + j_{b,min}}{2}}\right) \times 100$$





Angular Variation of Electron Density

- Plasma density tended to decrease with clock position, moving CCW from cathode
  - Appears as if there is an ionization front emanating from the cathode but with a sense—CCW
- Under some conditions, the density profile midplane was actually constant
- Langmuir data consistent with downstream button probe data



Angular Variation of Electron Temperature

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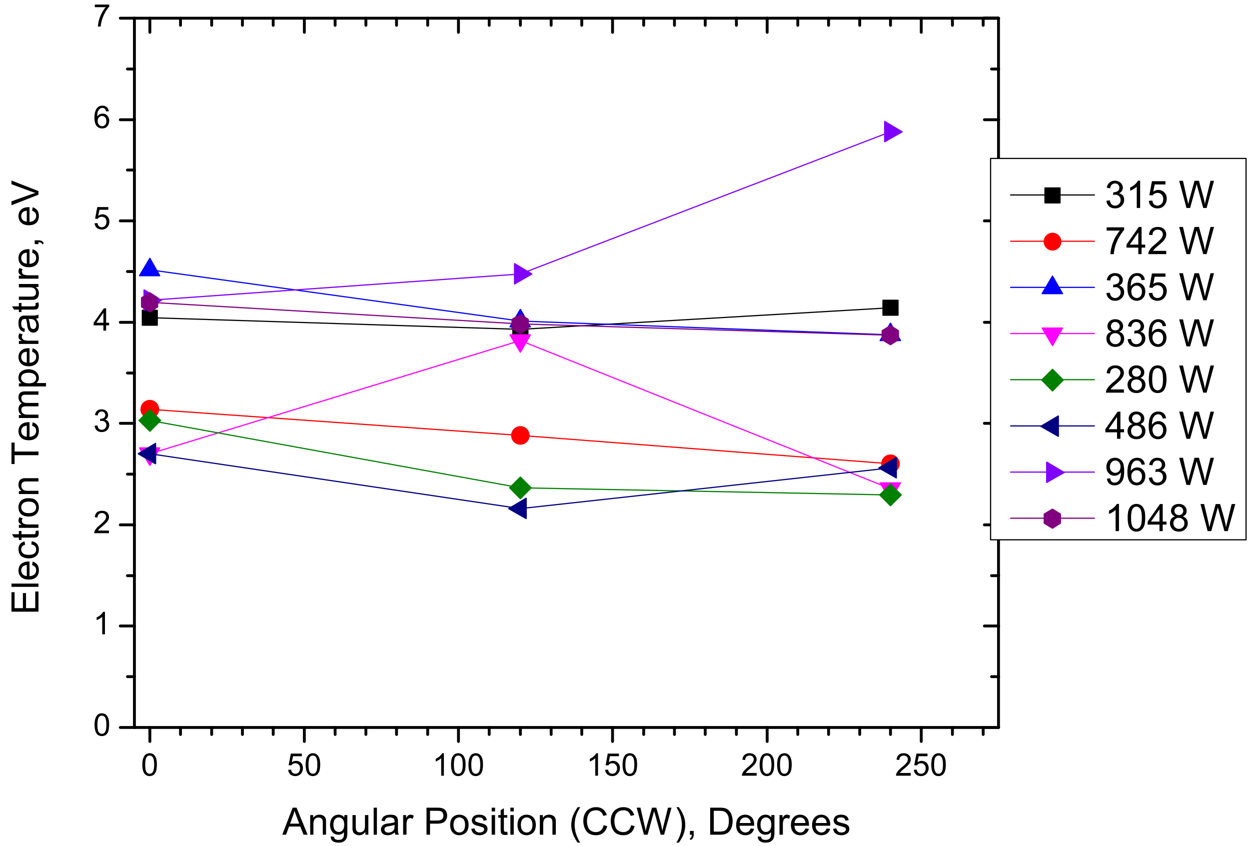
- Te to first order was roughly constant within experimental uncertainty (25 percent)
- The magnitude of the electron temperature did not manifest any noticeable trend—it simply ranged between 2-5 eV



FY15 Forward Plan

1. Complete the assembly of the 65 cm Annular Ion Optics

2. Complete the 20 kW Power Console

3. Complete the assemble the GEN2 AE

4. Characterize performance of GEN2 AE from ~3-20 kW, with emphasis on low specific impulse operation at high T/P; to include documentation of beam divergence to establish BETA for the flat ion optics

Summary

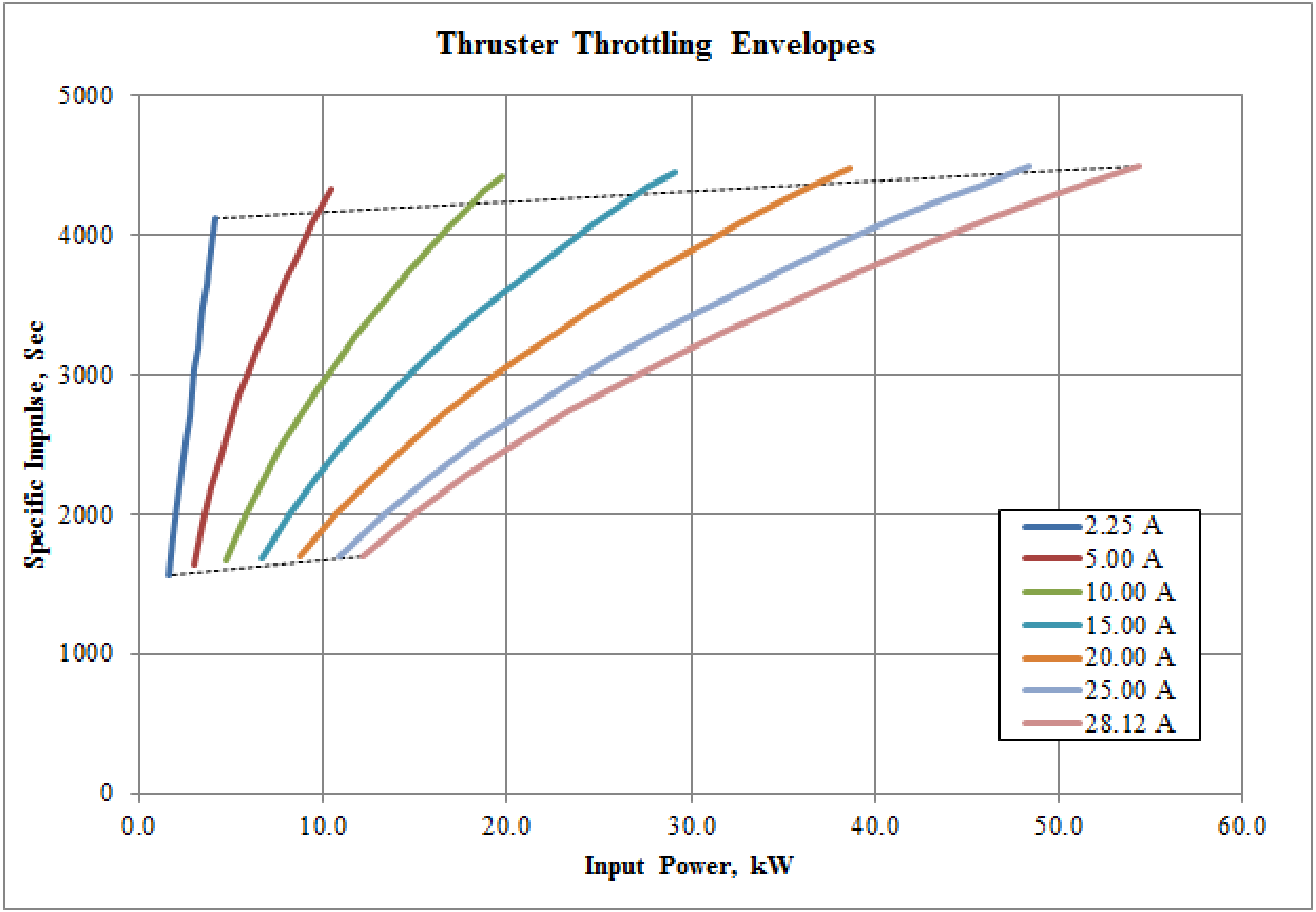
- SOA Ion thrusters are limited to about 10-15 kW at < 5,000 seconds Isp due to limitations in the ability to scale high-perveance ion optics to large areas

- The Annular Engine approach allows for a practical means of increasing the input power capability of ion thruster technology at low Isp by limiting the required maximum span-to-gap ratio of the ion optics

- Discharge chamber tests recently completed on GEN2 (65 cm) Engine
  - Excellent overall plasma uniformity in both radial and azimuthal directions with high discharge stability over very large range of discharge currents

- Performance testing and characterization of the GEN2 Engine will commence in early FY15

Anticipated AE Performance (65 cm O.D.)



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